What Do We Know about the Top Quark?

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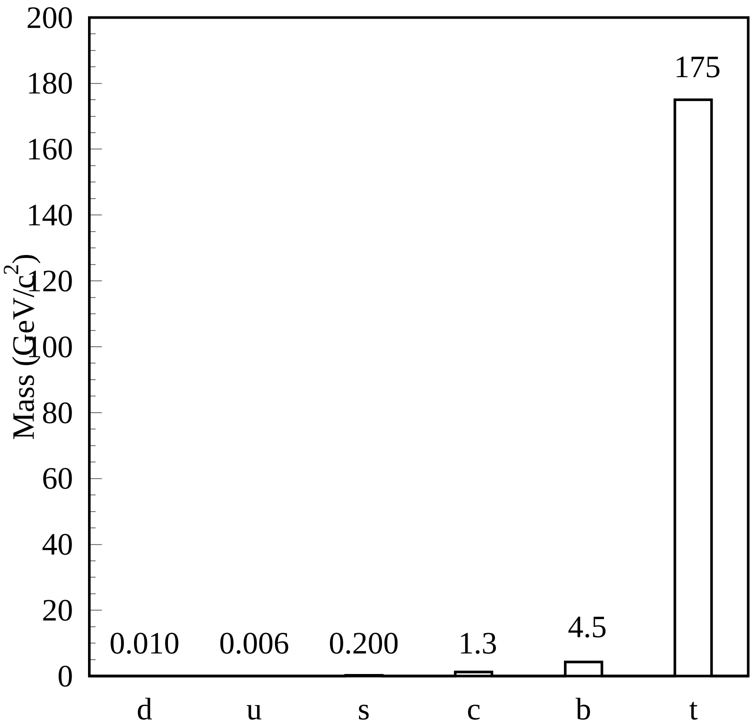
Outline:

- Introduction
- Top Quark Production and Detection
- Properties
  - $\sigma_{t\bar{t}}$ Measurements
  - M_{top} Measurements
  - V_{tb}
  - Search for Rare Decays
- Top Prospects Before the LHC
- Summary

Introduction

- **Top physics is less than three years old**, so we want to learn as much as possible.
- **Measurements of Standard Model Parameters like M_{Top}.**



- **Also, good place to look for extensions beyond the Standard Model.**

A Short History

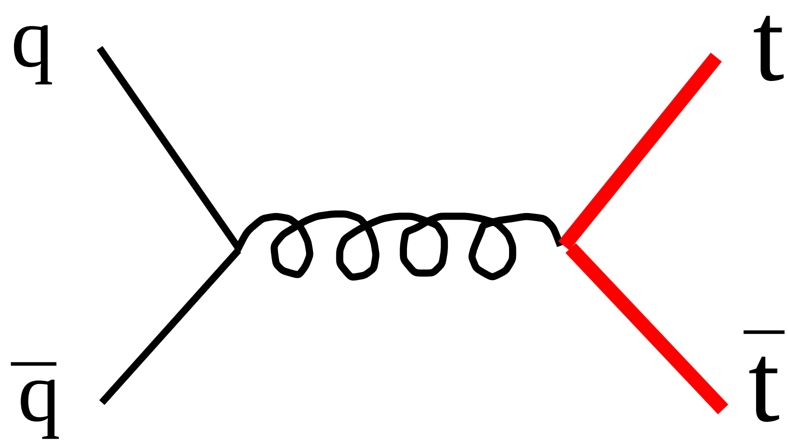
- 1977-1994: **A collection of null results**

- April, 1994: **First Evidence**
  - **Phys. Rev. D50, 2966 (1994)** CDF
  - 15 events on a background of 6.0
  - 2.8 σ excess
  - $M_{top} \ = \ 174 \pm 17 \ GeV/c^2$
  - $\sigma_{t\bar{t}} \ = \ 13.9^{+6.1}_{-4.8} \ pb$

- February, 1995: **Confirmation**
  - **PRL 74, 2626 (1995)** CDF
  - 4.8 σ excess
  - $M_{top} \ = \ 176 \pm 8(stat) \pm 10(syst) \ GeV/c^2$
  - $\sigma_{t\bar{t}} \ = \ 6.8^{+3.6}_{-2.4} \ pb$
  - **PRL 74, 2632 (1995) DØ**
  - 4.6 σ excess
  - $M_{top} \ = \ 199^{+19}_{-21}(stat)^{+14}_{-21}(syst) \ GeV/c^2$
  - $\sigma_{t\bar{t}} \ = \ 6.4 \pm 2.2 \ pb$

Top Production at the Tevatron

Top quarks are predominantly produced in pairs by the processes $p\bar{p} \rightarrow t\bar{t}$:.



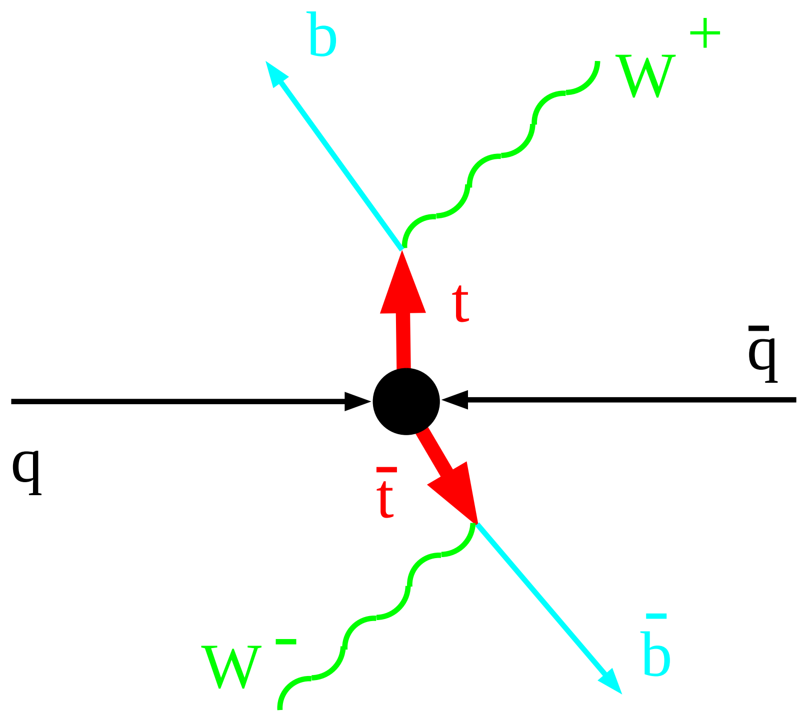
In Tevatron Run I, For both DØ and CDF:

- $\int Ldt$ exceeded 100 pb^{-1}
- over 5×10^{12} $p\bar{p}$ collisions
- $\approx$ **500** $t\bar{t}$ **pairs produced.**

$$\frac{\sigma_{\mathbf{t\bar{t}}}}{\sigma_{\mathbf{inel}}} \sim \mathbf{10^{-9}}, \qquad \frac{\sigma_{\mathbf{t\bar{t}}}}{\sigma_{\mathbf{W}}} \sim \mathbf{10^{-3}}$$

- Single top production through Wg fusion and W^* production is about 20% of this rate, and has not yet been observed.

Top Quark Decay Signatures



- Signature depends primarily on the decay of the W's
- Both W's Decay $W \to \ell\nu$ (Dilepton Channel)

Final State: $\ell^+\nu\ell^-\nu b\bar{b}$ (ℓ: e or μ; 5%)

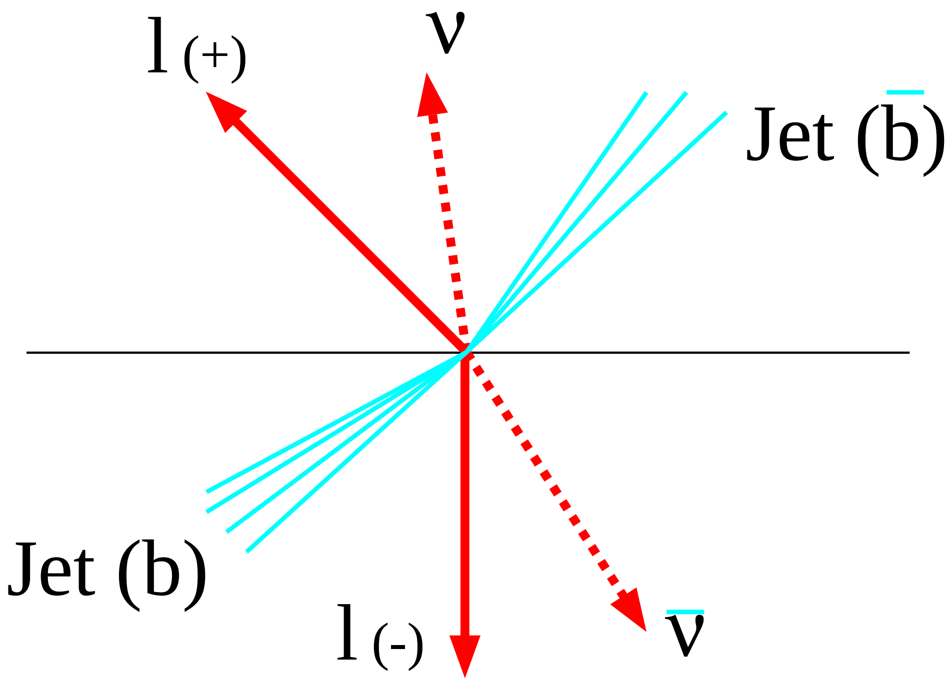
- One W Decay $W \to \ell\nu$ (Lepton+Jets Channel)

Final State: $\ell^+\nu\ q\bar{q}'\ \ b\bar{b}$ (ℓ: e or μ; 30%)

- Channels with $W \to \tau$ or both W's decaying $W \to q\bar{q}'$ have much higher backgrounds.

Starting to use these channels.

Dilepton Channels



- **Signature:**
  - Two isolated high P_T leptons (e, μ, τ)
  - Missing Energy ($\not\!\!E_T$) from two ν's.
  - 2 or more jets
- **Dominant Backgrounds:**
  - WW
  - $Z \rightarrow \tau\tau$
  - Fake leptons
  - Drell Yan
- **Features:**
  - Good Signal-to-background ratio but low statistics
  - Not ideal for top mass determination (two ν's)

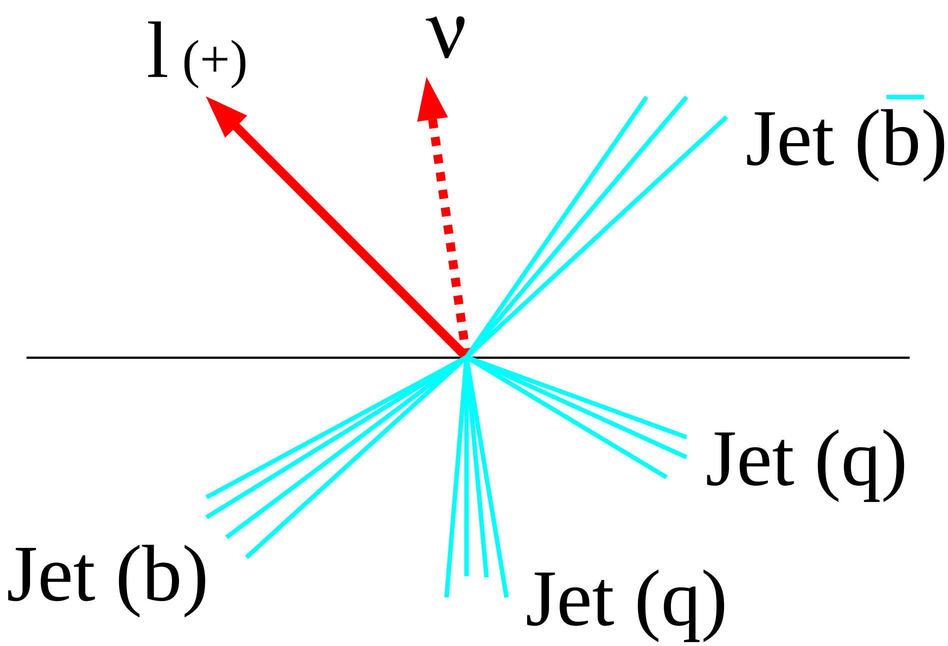
Dilepton Event Summary

Sample	DØ	CDF
$e\mu$	3	7
Background	0.4 ± 0.1	0.76 ± 0.21
Expected Yield	1.7 ± 0.3	2.4 ± 0.2
($M_{top} = 175$ GeV/c^2)		
ee or $\mu\mu$	2	2
Background	1.2 ± 0.4	1.23 ± 0.36
Expected Yield	1.4 ± 0.1	1.6 ± 0.2
($M_{top} = 175$ GeV/c^2)		
e *or* $\mu + \tau$	2	4
Background	1.4 ± 0.5	1.96 ± 0.35
Expected Yield	1.4 ± 0.1	0.7 ± 0.1
($M_{top} = 175$ GeV/c^2)	(88 pb^{-1})	

Sample Selection Relies on:

- High E_t Leptons
- Jet Activity
- Missing Energy
- Kinematic Cuts (H_t, Angular distributions)

Lepton + Jets Channels



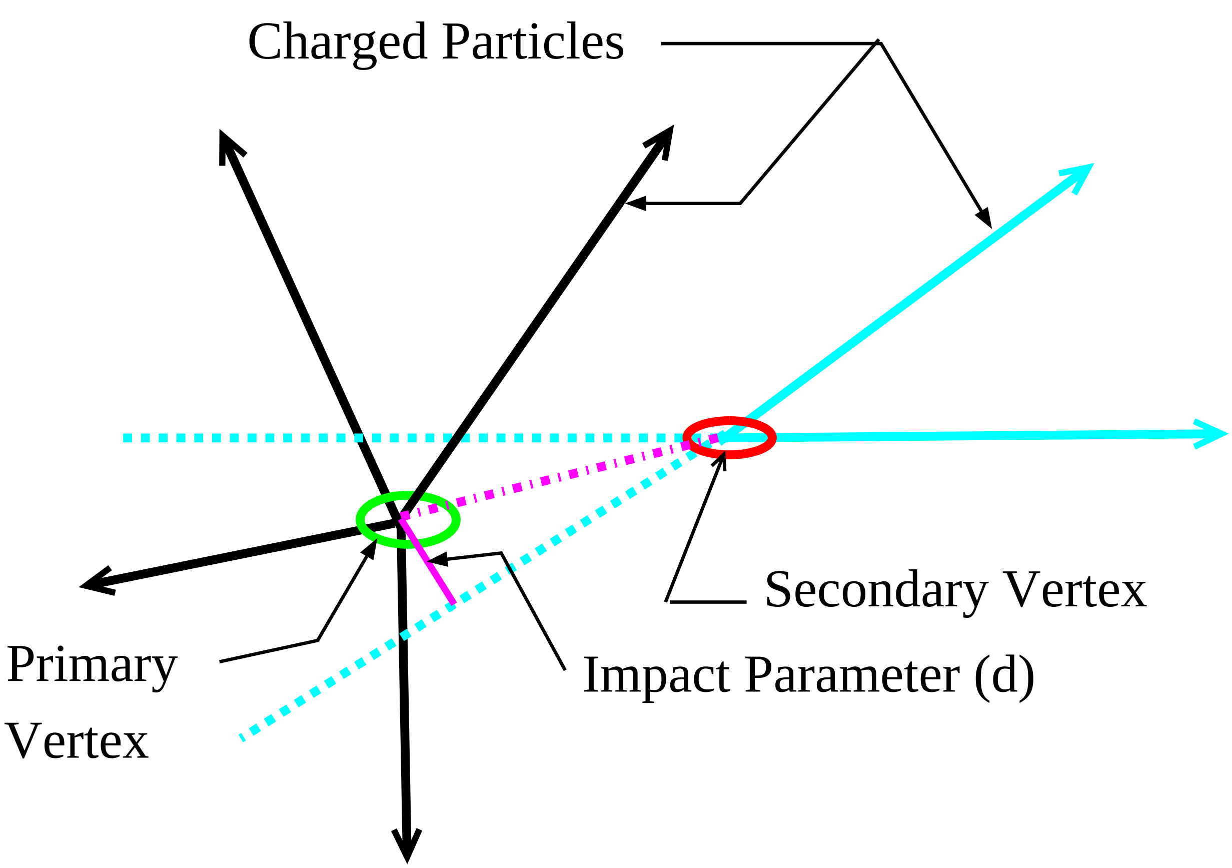
- **Signature:**
  - One isolated high P_T lepton (e or μ)
  - Missing Energy ($\not{E}_T$)
  - 4 or more jets, 2 of which are from b-quarks
- **Dominant Backgrounds:**
  - $p\bar{p} \rightarrow W + jets$
  - QCD background (Fake leptons)

Reduction of Background:

- Cut on Event Shape:
  - Aplanarity (Planar (0) $> \mathcal{A} >$ Spherical (1/2))
  - $\Sigma H_T = \Sigma E_T(Jets)$
  - Form Likelihood ($t\bar{t}$ vs. Back.) based on jet E_T's
- Tag b-quarks using semileptonic Decay

$$b \to \mu X \quad (20\%), \qquad b \to eX \quad (20\%)$$

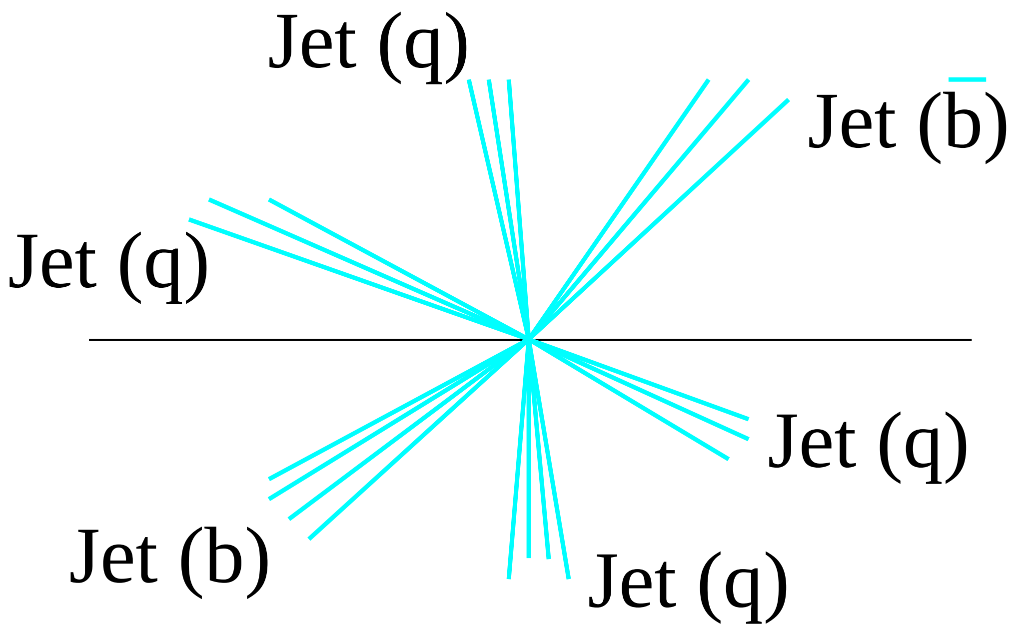
- Tag b-quarks by displaced vertex (CDF)



Summary of Lepton+Jets Events

Sample	DØ	CDF
Event Shape:		
Observed	21	22
Background	9.2 ± 2.4	7.2 ± 2.1
Expected Yield	12.9 ± 2.1	-
($M_{top} = 175$ GeV/c^2)		(Based on 67 pb^{-1})
$b \to \ell X$:		
Observed	11	40
Background	2.5 ± 0.4	24.3 ± 3.5
Expected Yield	5.2 ± 1.0	9.6 ± 1.7
($M_{top} = 175$ GeV/c^2)		
Displaced Vertex:		
Observed	-	34
Background	-	8.0 ± 1.4
Expected Yield	-	19.8 ± 4.0
($M_{top} = 175$ GeV/c^2)		

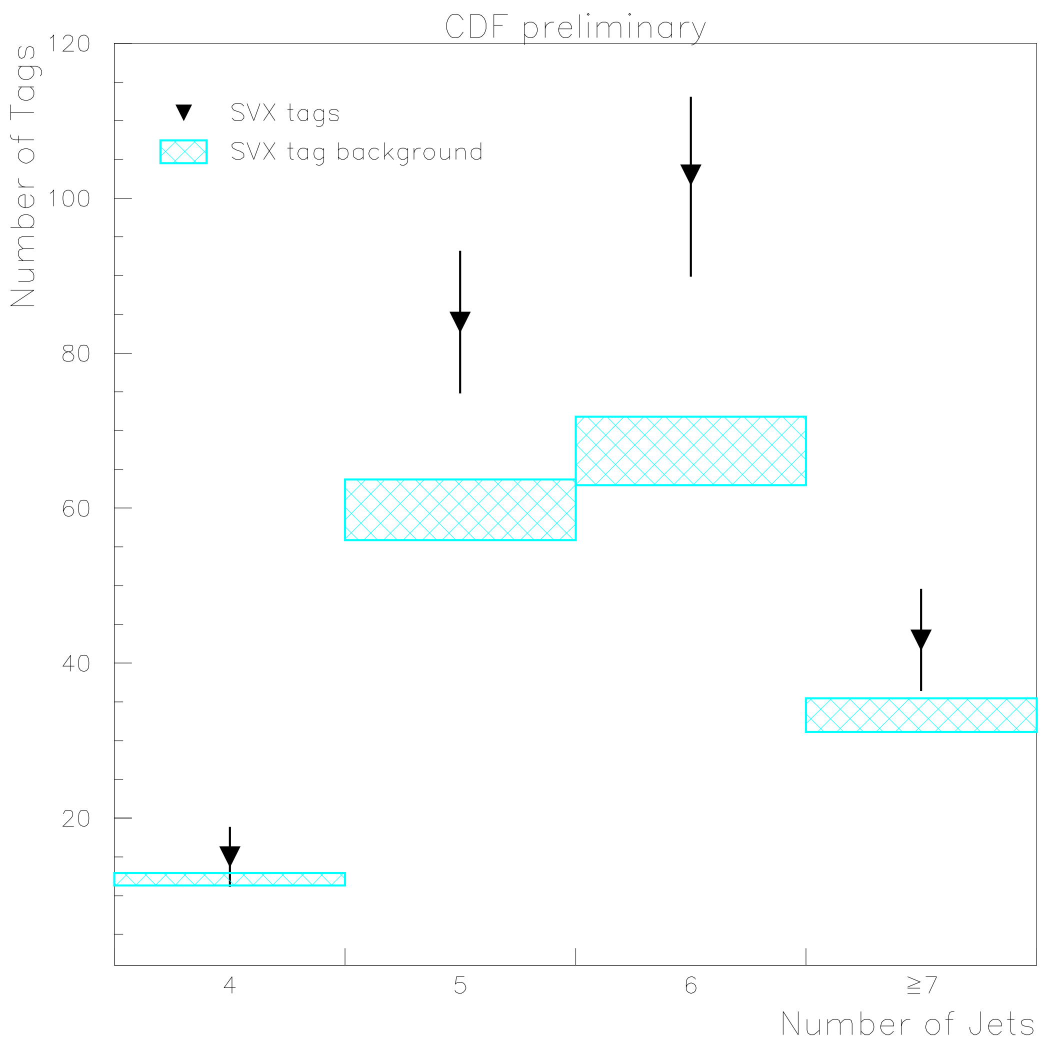
<u>All Hadronic Channel</u>



- **Signature:**
  - 6 or more jets, 2 of which are from b-quarks
  - not all 6 jets are always observed
- **Dominant Backgrounds:**
  - QCD multijet production
- **Features:**
  - Signal-to-background is $\sim \frac{1}{30}$ before additional topological/kinematic requirements or b-tagging
  - If background can be controlled, top mass determination possible (no neutrinos)

All Hadronic Event Summary

Sample	DØ	CDF
Observed	15	192
Background	11 ± 2	137.1 ± 11.3
Expected Yield	4.5 ± 0.5	26.6 ± 9.1
($M_{top} = 175$ GeV/c^2)		



We have:

$\approx$ 13 dileptons
$\approx$ 70 Lepton+Jets
$\approx$ 60 All Hadronic

Now what do we want to learn?

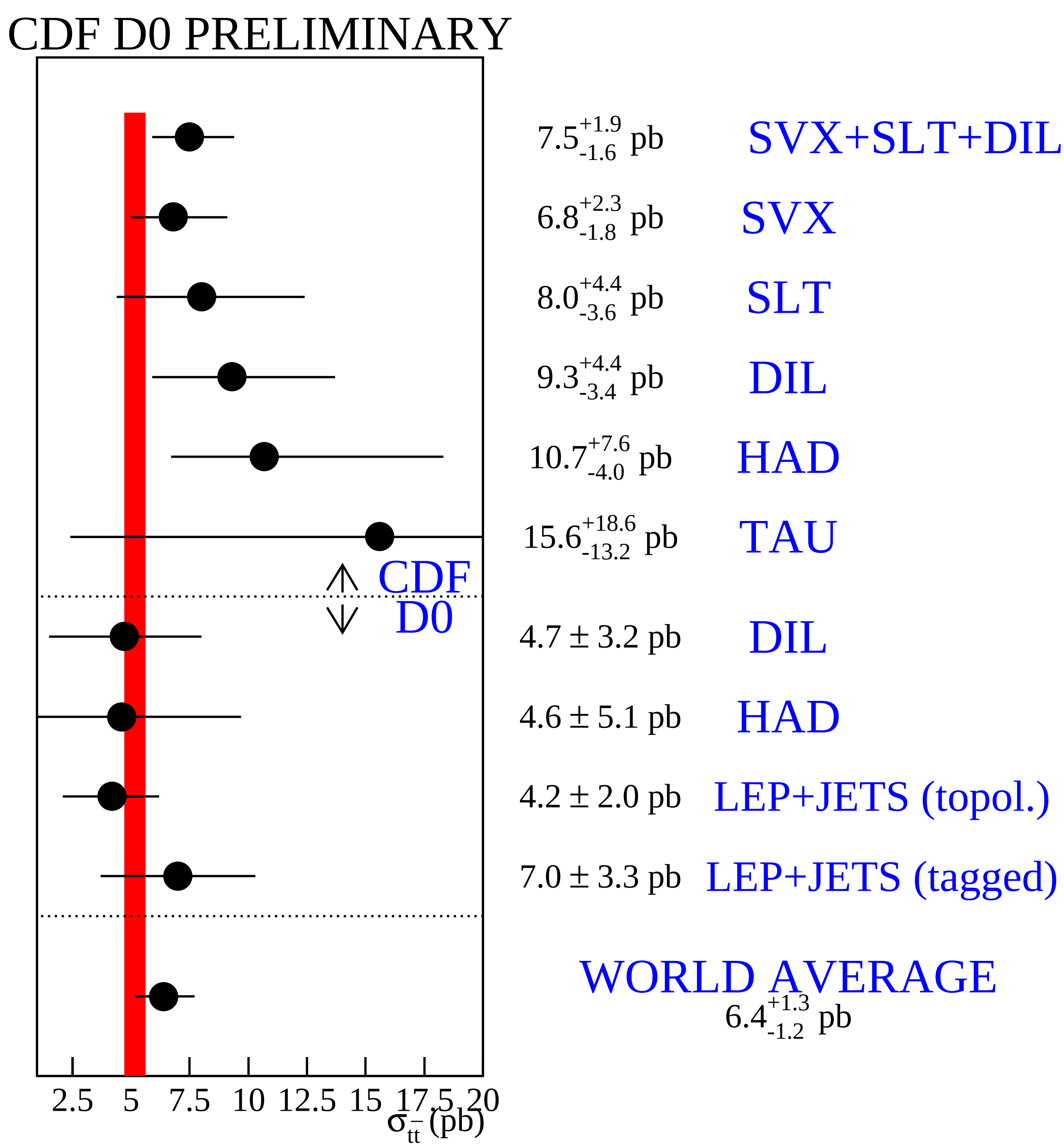
- Production Properties (e.g. $\sigma_{t\bar{t}}$)
- Decay Properties (e.g. V_{tb})
- Top Quark Mass (M_{top})

$t\bar{t}$ Cross Section Measurement

- This measurement is straight forward.

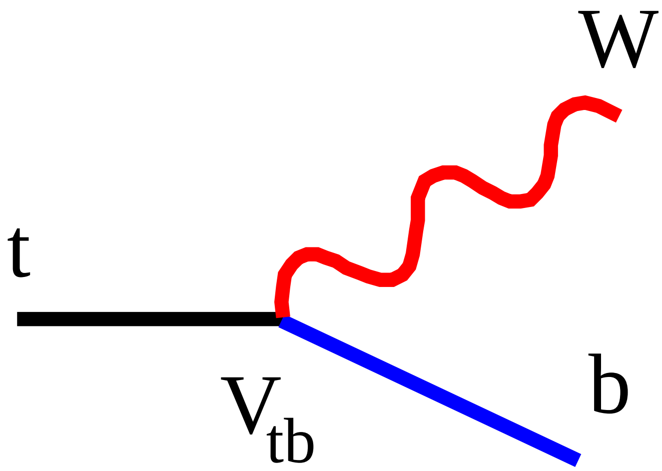
$$\sigma = \frac{N_{obs} - N_{bkg}}{A\mathcal{L}}$$

- The measurement can be made in each decay channel individually and compared with one another and to a theoretical prediction.



Width of theory band given by spread in Laenen et al, Berger et al, Nason et al, and Catani et al, at 175 GeV/c^2

CDF Measurement of V_{tb}



- Unitarity within a three-generation Standard Model implies $V_{tb} \sim 1.0$
- CDF has analyzed the $l + jets$ and dilepton samples to:
  - Measure the ratio of events with 0, 1, and 2 b-tags
  - Use this to extract

$$b = \frac{Br(t \rightarrow Wb)}{Br(t \rightarrow WX)}$$

- By comparing ratios of these event yields, this result is independent of the value of $\sigma_{t\bar{t}}$ and $\frac{Br(W \rightarrow l\nu)}{Br(W \rightarrow q\bar{q})}$

Results of a maximum likelihood Combining all Information

$$\mathbf{b} \;=\; \frac{\mathbf{Br(t \to Wb)}}{\mathbf{Br(t \to WX)}} \;=\; \mathbf{0.94 \pm 0.27(stat)} \;\; \mathbf{\pm 0.13(syst)}$$

$$\mathbf{b} \;\; > \mathbf{0.34 \text{ at } 95\% \text{ c.l.}}$$

In a three-generation Standard Model,

$$b \;=\; \frac{|V_{tb}|^2}{|V_{td}|^2 \;+\; |V_{ts}|^2 \;+\; |V_{tb}|^2}$$

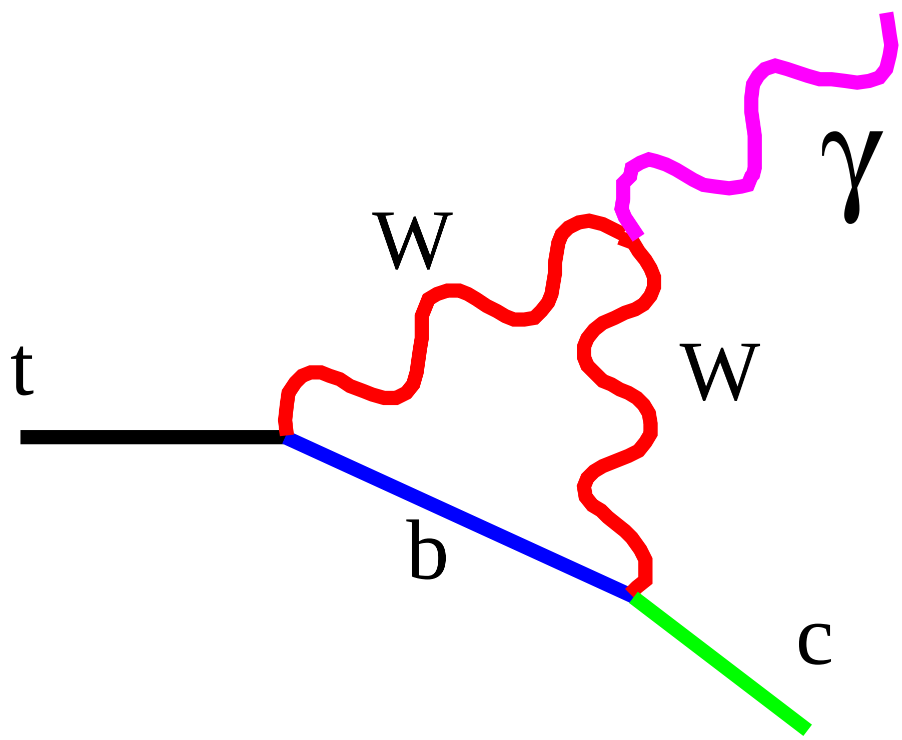
Assuming 3-generation unitarity this yields:

$$|\mathbf{V_{tb}}| \;=\; \mathbf{0.97} \;\pm\; \mathbf{0.15} \;\pm\; \mathbf{0.07}$$

and

$$|\mathbf{V_{tb}}| \;\; > \mathbf{0.58 \text{ at } 95\% \text{ c.l.}}$$

Search for Rare Decays



- Search $t\bar{t}$ events for one top decaying in the standard fashion ($t \to Wb$) and the other top quark decaying to a rare mode:
  - $t \to \gamma\ c$, $\quad t \to \gamma\ u$ (BR $\approx 10^{-10}$)
  - $t \to Zc$
  - $t \to WZb$
- Expect nothing and limit will be not be a strong test of the standard model, but....
- A Preliminary search for $t \to \gamma\ q$ by CDF yields:

$$BF(t \to c\gamma)\ +\ BF(t \to u\gamma)\ <\ 2.9\%\ \ (95\% C.L.)$$

Measuring the Top Mass

- M_{top} is a standard model parameter.
- Most important measurement from this run.

- Goal: Determine M_{top}
  - as accurately as possible
  - using as many decay modes as possible
  - using several methods to cross check techniques, systematics, etc.

- Amazing amount of work by both experiments on exploring these issues.
- Measurements significantly improved since last papers (Feb 1995) and even since winter conferences.
  - δM_{top} (DØ) $\approx 2.5\times$ better
  - δM_{top} (CDF) $\approx 2\times$ better

We've got it surrounded

L + Jets

* Kinematic Reconstruction
* Modified
  -- Subsamples
  -- Optimized
  -- Adding additional constraints

M_{TOP}

Dilepton

* Likelihood (D0)
  => Mass = 158 +/- 26 GeV
* < M_{lb} > (CDF)
  => Mass = 162 +/- 22 GeV
* < E_T^b > (CDF)
  => Mass = 160 +/- 28 GeV

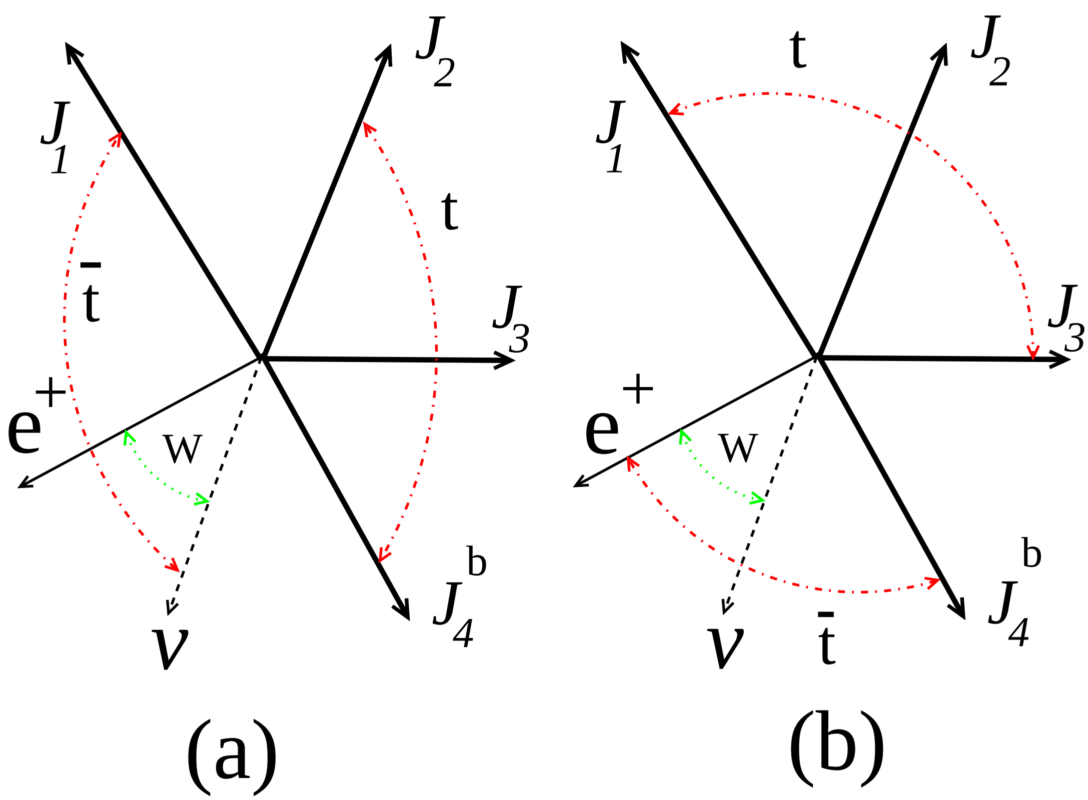
All Hadronic

* Kinematic Reconstruction

* Mass = 187 +/– 15 GeV (CDF)

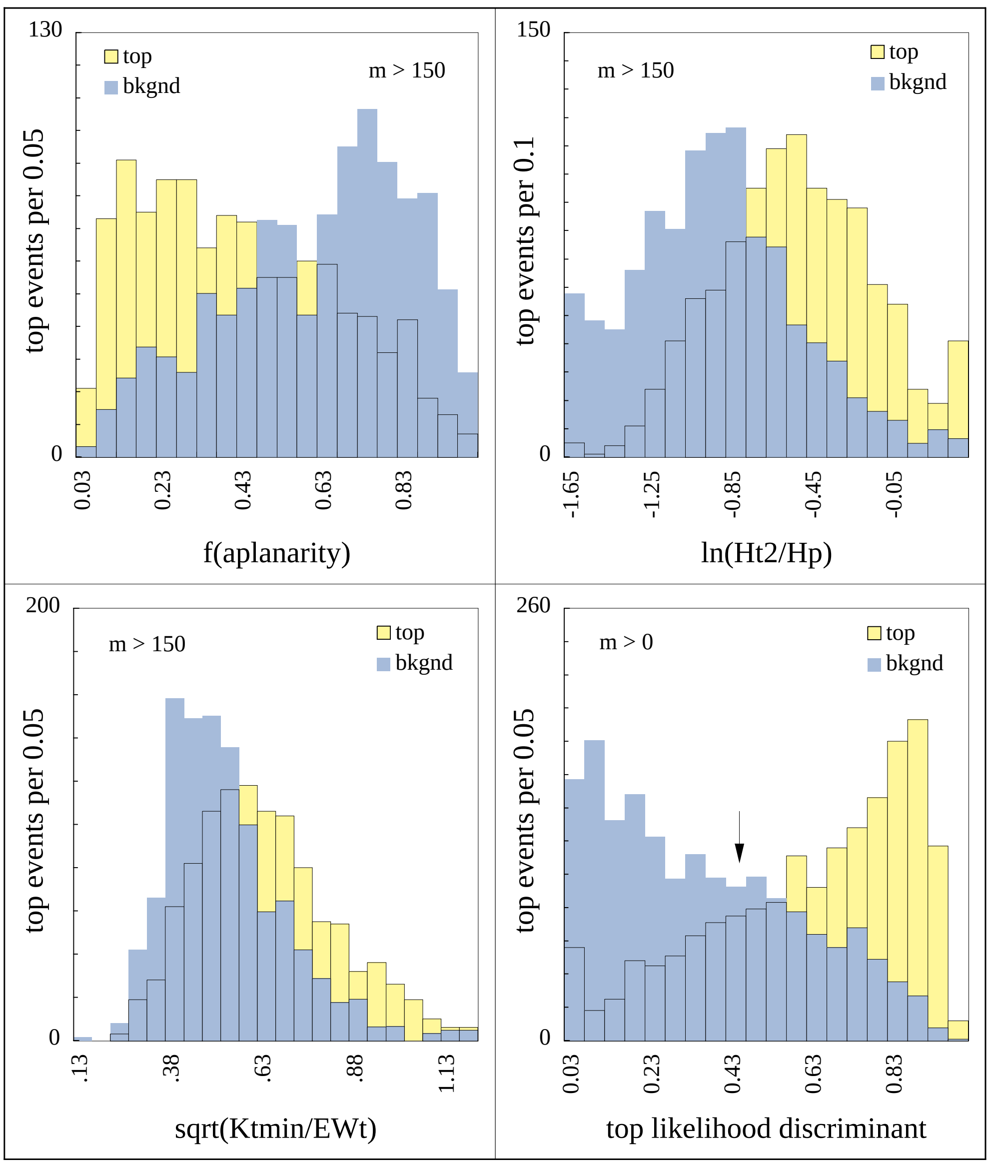
Mass using Lepton+Jets Events

- Decay mode with most power
- Attempt to reconstruct the top quarks from the decay products.
- Problem: Events are $t\bar{t} + X$; naively we don't know how to assign the observed objects to the t and $\bar{t}$



- 24 Total Combinations (12 w/ 1 b-tag, 4 w/ 2 b-tag)
- Constraints: $M_{jj} = M_W$, $M_{top} = M_{antitop}$
- Pick best combination by forming a χ^2
  - Wrong combinations peak at M_{top}

- Power to extract M_{top} depends on S/B in the sample.
- DØ combines 4 kinematic variables into 1 discriminant D, which separates top from background. A fit in 2-dim. is performed to extract the best M_{top}.



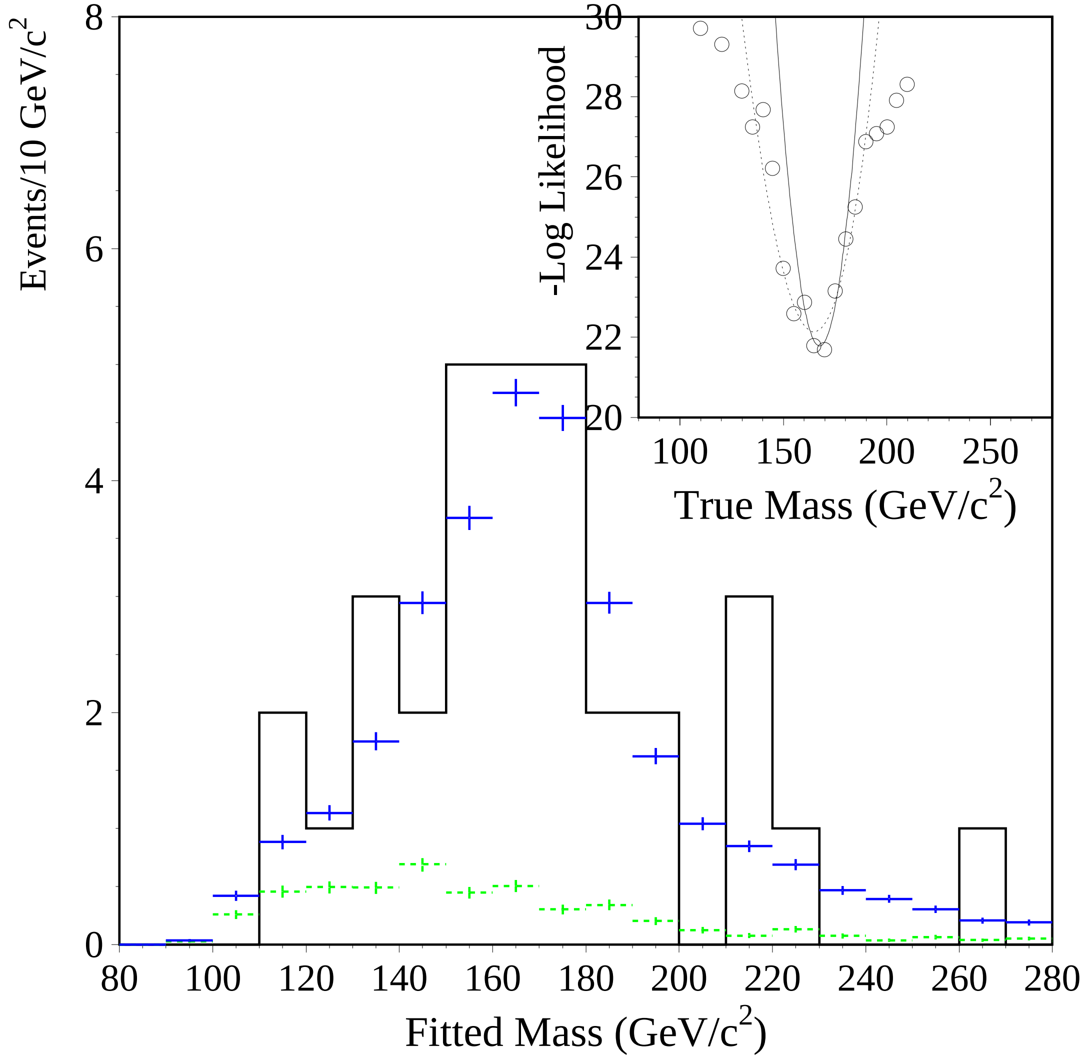
DØ Mass Fit

preliminary

2D fit to 32 events (LB sample)

constrain signal by PR fit

$m_{top} = 168 \pm 8(stat.),\ \chi^2 = 21.7/22$



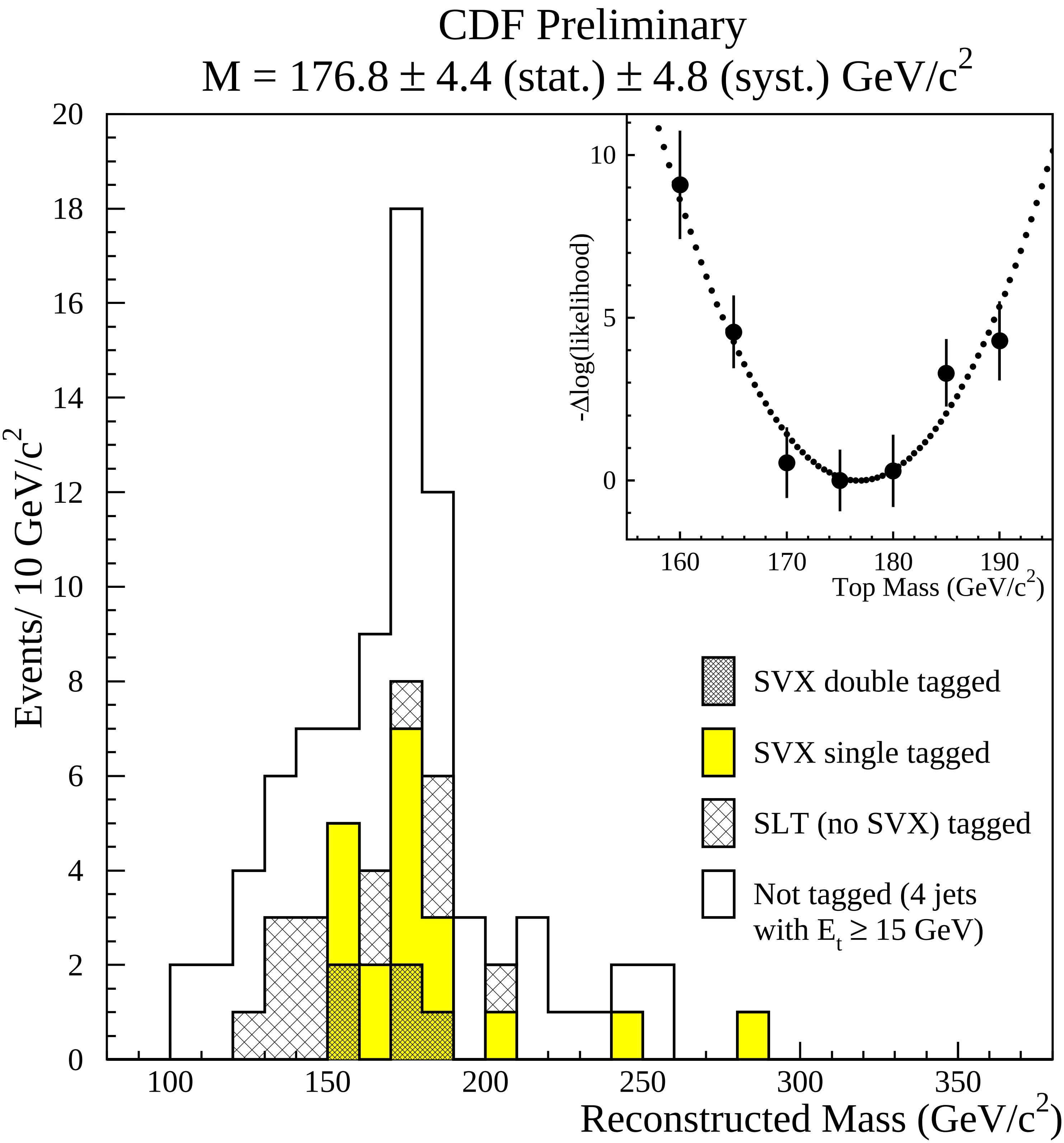
+ background, + signal+background

- CDF has good S/B with Displaced Vertex (SVX) tagging

- Recent optimization studies show dividing the lepton+jets into 4 independent samples yields the best result.
  - Each fit independently
  - Best mass found using the likelihood from each.

- Samples:
  1. One Displaced b-tag
  2. Two displaced b-tags
  3. One or more $b \to \ell X$ (no displaced tag)
  4. No b-tags (4 Jets w/ $E_T \geq 15$ GeV)

CDF Results



CDF Preliminary
M = 176.8 ± 4.4 (stat.) ± 4.8 (syst.) GeV/c²
Events/ 10 GeV/c²
Reconstructed Mass (GeV/c²)
0
2
4
6
8
10
12
14
16
18
20
100
150
200
250
300
350
-Δlog(likelihood)
Top Mass (GeV/c²)
0
5
10
160
170
180
190
SVX double tagged
SVX single tagged
SLT (no SVX) tagged
Not tagged (4 jets
with E_t ≥ 15 GeV)

Tables of Systematics on the Lepton+Jets Sample

CDF L+Jet Mass Systematic	Value GeV/c^2
Soft Gluon + Jet E_T Scale	3.6
Different Generators	1.4
Hard Gluon Effects	2.2
Kinematic and Likelihood Fitting Methods	1.5
b-tagging Bias	0.4
Background Spectrum	0.7
Monte Carlo Statistics	0.8
Total	4.8

DØ L+Jet Mass Systematic	Value GeV/c^2
Jet Energy Correction	± 7.3
Monte Carlo Model	± 3.3
Fitting Method	± 2.0
Total	8

Combining CDF and DØ Top Mass Measurements

- Used only Lepton+Jet Mass Measurements
  - CDF: 176.8 ± 4.4 ± 4.8 GeV/c^2
  - DØ: 169 ± 8 ± 8 GeV/c^2

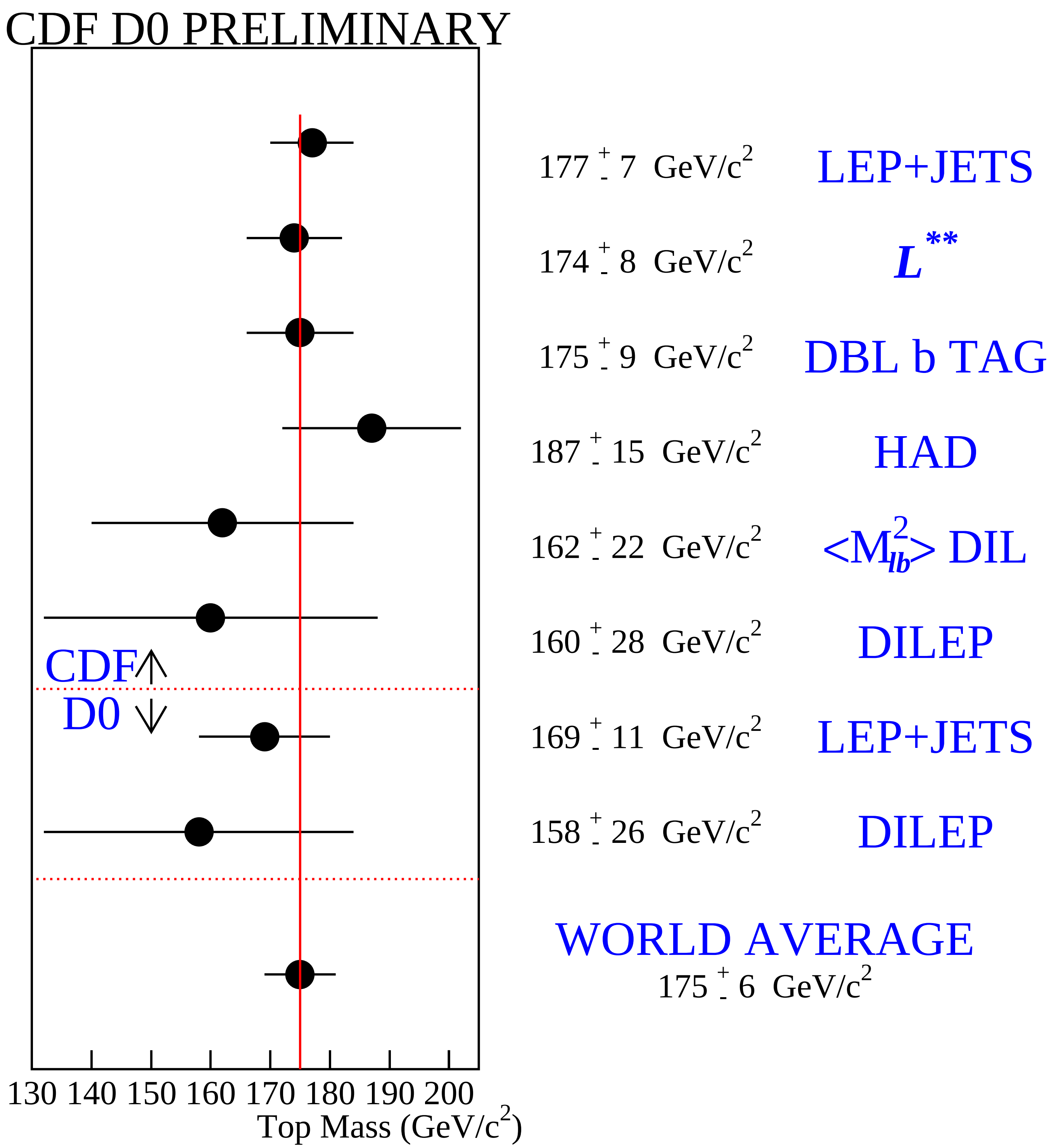
- Assumptions:
  - Made the conservative assumption that all the systematic errors, except energy scale, b-tagging bias and Monte Carlo statistics, are 100% correlated.
  - Found the central value by weighting by the statistical error only.

- Results:

$$M_{top} = 175.0 \pm 3.9 \pm 4.5 \ \mathrm{GeV/c^2}$$

$$\mathbf{M_{top} = 175 \pm 6 \ GeV/c^2}$$

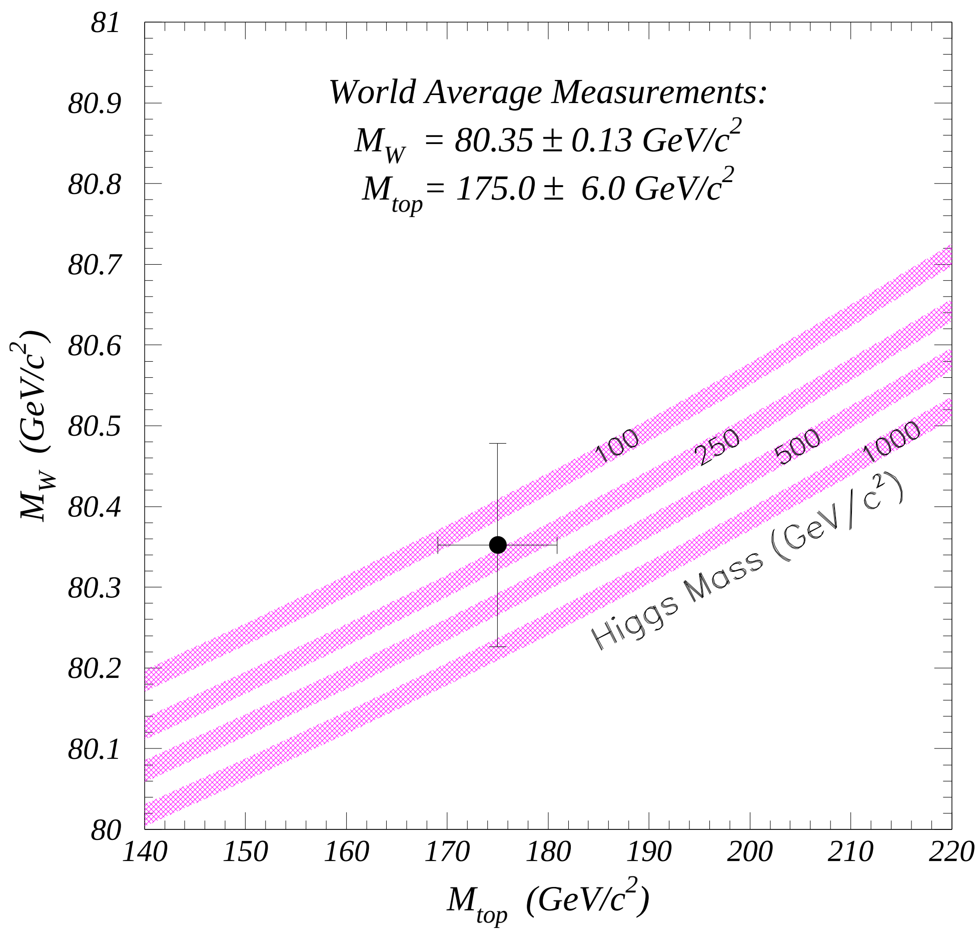
Summary of Mass Measurements



$\underline{M_{top} \quad and \quad M_W}$

- The top quark mass and the W boson mass can tell us something about the Higgs mass, if we can measure M_{top} and M_H precisely enough.

M_W vs. M_{top}



Need More Data!

Future Prospects Before LHC

- Tevatron Upgrades:
  - Main Injector Commissioning
  - $E_{cm} = 2.0$ TeV ($\sigma_{t\bar{t}}$ 40% higher)
  - $\mathcal{L} = 2.0 \times 10^{32}$
  - $\int$ L = 2 fb^{-1} (Factor 20 increase)
- Detector Upgrades:
  - Enhance the efficiency to detect top decays (*e.g.* CDF/DØ Long Silicon Vertex Detectors)
- Estimate Yields: (per experiment)
  - Dileptons: 160
  - L+Jets + $\geq$ 1 b-tag: 990
  - L+Jets + $\geq$ 2 b-tag: 450
- Projected Results (See FERMILAB–PUB–96/082)
  - $\delta M_{top} = 1 - 2$ GeV/c^2
  - $\delta\sigma_{t\bar{t}} = 9\%$
  - Study of single top production
  - Polarization studies

Summary

- Top has been observed and $\sigma_{t\bar{t}}$ has been measured in many decay modes:

$$\mathbf{t\bar{t} \rightarrow W + Jets + X}$$
$$\mathbf{t\bar{t} \rightarrow W + b + Jets + X}$$
$$\mathbf{t\bar{t} \rightarrow l^{+}l^{-} + Jets + X}$$
$$\mathbf{t\bar{t} \rightarrow l^{+}} + \tau + \mathbf{Jets + X}$$
$$\mathbf{t\bar{t} \rightarrow 6\ Jets + X}$$

- World Average Top Cross Section at 175 GeV/c^2:

$$\sigma_{\mathbf{t\bar{t}}} = \mathbf{6.4^{+1.3}_{-1.2}\ pb}$$

QCD predictions range from 4.7 to 5.6 pb

- New Top mass results emphasize optimal use of information and are much more precise:

$M_{Top} = 169 \pm 11\ GeV/c^2$ DØ L+jets
$M_{Top} = 176.8 \pm 6.5\ GeV/c^2$ CDF L+jets

$M_{Top} = 175 \pm 6\ GeV/c^2$ CDF/DØ L+jets

Nothing observed in top production or decay is glaringly inconsistent with the Standard Model.